British Heart Journal, 1978, **40**, 1344-1348

Effects of recording speed on precision of time-based polycardiographic measurements[1]

Optimal paper speeds for measuring points and intervals

DAVID H. SPODICK, HARRISON G. BALL, AND VERONICA M. PIGOTT

From the Cardiology Division, St Vincent Hospital; the Departments of Cardiovascular Medicine and Medicine, University of Massachusetts, School of Medicine, Worcester, Massachusetts; and the Department of Medicine, Tufts University School of Medicine, Boston, Massachusetts, USA

SUMMARY Optimal paper speeds have not been established for all time-based measurements of the cardiac cycle by appropriately designed observer performance studies. In 10 subjects (5 normals and 5 cardiac patients) carotid pulse, phonocardiogram, and electrocardiogram were recorded on magnetic tape for measurement of all fiducial points for systolic time intervals, the systolic time intervals themselves, the pulse transmission time, cycle length (RR), qR time, and R-to-point versus q-to-point measurements at recording speeds of 25, 50, 75, 100, and 200 mm/s. Tracings were coded numerically and randomised. Three observers measured all points and calculated intervals in a sequence determined by individual tables of random numbers. Left ventricular ejection time was the only calculation that could be made at 25 mm/s statistically equally well as at all other speeds. The smallest numerical observer differences occurred uniformly at 100 mm/s paper speed when all recording speeds were considered. However, after excluding the 25 mm/s speed there were no significant differences among point measurements. Measurements of points from R (rather than q) reduced observer variability. We conclude that for point measurements, for systolic time intervals, pulse transmission time, and RR interval, recording speed between 50 and 200 mm/s showed no statistical differences, though smallest numerical differences occurred at 100 mm/s. For LVET, 25 mm/s was satisfactory.

The precision of time-based measurements (physiologically significant landmarks and intervals) of the cardiac cycle is largely a function of observer performance, which in turn depends on point recognition and interpolation with the time scale. A variety of standard recording paper drives is available, with hypothetical advantages at faster paper speeds and convenience and economy at slower paper speeds. While interpolation should be facilitated at faster speeds and the resolving power of the eye should be limited at slower speeds, differences in point recognition may modify these effects. Thus, less well-defined points can be excessively dragged out at faster speeds, for example transition from slow to rapid arterial pulse upstroke. Actual performance of representative observers under controlled conditions with biases minimised would bypass *a priori* theoretical considerations as a valid comparative test of a range of paper speeds. Apparently only three observer performance studies have been reported, two restricted to measurements of left ventricular ejection time (Spodick *et al.*, 1969; Lewis *et al.*, 1977) and one to apex cardiography (Pigott *et al.*, 1972). Only the study on apex cardiograms was reported as randomised to reduce observer bias.

We designed a multi-observer, blind, and randomised study to identify the recording speed(s) which is (are) optimal for measuring all the fiducial points of measurement as well as for each of the calculated systolic time intervals and related measurements. For this study, optimal recording speed is defined as the speed or speeds at which measurements by representative trained observers showed the least variability.

Subjects and methods

We investigated each individual point of measurement for systolic time intervals, the systolic time intervals themselves, the central pulse transmission time, and heart rate (as cycle length = RR), using 3 experienced observers, at paper speeds of 25, 50, 75,

[1]Supported by a NASA grant.
Received for publication 19 January 1978

100, and 200 mm/s. The carotoid displacement pulse, apical phonocardiogram, and electrocardiogram were recorded in 10 subjects aged 25 to 79 years (5 normal volunteers and 5 cardiac patients) on a Hewlett-Packard No. 3960 4-channel FM magnetic tape recorder. The tapes were then played into a Hewlett-Packard No. 4560 optical polygraph with print-out at the selected speeds. Time lines were generated at 40 ms.

STANDARDISATION, RANDOMISATION, AND BLINDING

Tracings were segmented for each subject and each speed for a total of 50 segments. The identical 5 cycles for each subject were designated on each segment. This procedure permitted an identical group of complexes to be recorded for each subject at all 5 paper speeds, thus eliminating changes in complex configuration and timing at different speeds caused by both patient beat-to-beat variability and any possible instrumentation instability. Segments were coded for identification and then randomised after which they were numbered '1' to '50'. Each observer then used a different table of random numbers to select the order in which segments would be measured. Thus, there was complete randomisation so that no subject's recordings were read sequentially. After all measurements were recorded, the codes were broken and the results submitted to analysis of variance. Optimal paper speed for a given measurement was considered that speed at which inter-observer variability was minimal.

MEASUREMENTS AND CALCULATIONS

Numerical results were tabulated to the nearest 5 ms for the following points and for cycle length. The remaining intervals were derived from the points as indicated.

Point measurements

Q to peak of the R wave (R); Q to the first high frequency oscillation ('mitral' component) of the first heart sound (I_M); Q to the onset of the rapid portion of the carotid upstroke (CAR_u); Q to the first high frequency (aortic) component of the second heart sound (II_A); Q to the carotid incisura (CAR_{IN}).

Interval measurements

Cycle length expressed as the time from the peak of the R wave in the cycle measured to the peak of the preceding R wave (RR); pulse transmission time (PTT) defined as the interval between II_A and CAR_{IN}; pre-ejection period (PEP) defined as CAR_u minus PTT; isovolumic contraction time (IVCT) defined as PEP minus I_M; left ventricular ejection time (LVET) defined as the interval between the CAR_u and the CAR_{IN}.

SPECIAL CONSIDERATION OF QR TIME

'Zero time' for all point measurements in the cardiac cycle is the initiation of the Q wave of the electrocardiogram. In this study lead II was chosen for convenience, though it is understood that a 12 lead electrocardiogram or orthogonal leads may give an earlier zero point. We dealt with precision of measurements rather than absolute values and this difference would not affect precision.

It is common experience that the peak of the R wave is a much cleaner point and, therefore, more easily recognisable than the onset of the Q wave. Furthermore, because of perturbation of the electrocardiograph baseline, the width of Q waves in successive cycles is very often variable. For these reasons, it was decided before the study that all point measurements would be made in two steps. All complexes of a given subject at the paper speed under consideration were examined, and QR was determined by each observer. Each observer then measured all points from the R wave peak, and another set of values was calculated by adding the QR to these measurements. All measurements listed in this paper include the QR interval unless specifically stated that the QR interval has not been included.

The mean of the point measurements and the RR interval of the 5 designated beats for a given subject and speed was then calculated by each observer. The systolic time intervals were subsequently calculated from these means.

STATISTICAL ANALYSES

Analysis of variance was used to determine *intra*-observer variability among the 10 subjects and 5 paper speeds. *Inter*-observer variability was also examined by analysis of variance, but in this case the values examined were the differences between observers 1 and 2, observers 1 and 3, and observers 2 and 3. Since we were concerned with the magnitude of the difference between observers, all differences were expressed as absolute values irrespective of which observer made the greater reading. In this way, compensations between positive and negative differences were eliminated.

The paired observer differences were then examined for variability (a) among paper speeds, (b) among subjects, and (c) the three groups of paired observer differences. Additionally, (d) interactions among (a), (b), and (c) were determined.

Results

Results are summarised in Tables 1 to 6.

Table 1 *Mean paired observer differences at all 5 paper speeds**

	25 mm/s	50 mm/s	75 mm/s	100 mm/s	200 mm/s
Points					
R peak	8·3	5·7	5·0	4·3	5·3
I_M	13·5	12·2	11·1	12·2	9·5
CAR_u	11·5	6·3	5·9	5·3	6·2
II_A	8·8	7·7	6·7	6·4	6·1
CAR_{IN}	10·7	6·5	6·3	5·9	7·3
Total differences	52·8	38·4	35·0	34·1	34·4
Total − I_M	39·3	26·2	25·9	21·9	24·9
Intervals					
RR	4·6	7·5	3·8	1·7	2·6
PTT	4·0	2·7	4·1	2·6	2·5
PEP	10·7	7·3	6·1	5·2	5·3
IVCT	12·6	11·4	13·1	11·5	8·8
LVET	5·8	4·7	4·9	4·6	5·7
Total differences	37·7	33·6	32·0	25·6	24·9
Total − IVCT	25·1	22·2	18·9	14·1	16·9

*Differences expressed in ms.

OPTIMAL PAPER SPEED

Table 1 presents the means of the 3 paired observer differences at each of the 5 paper speeds for all 10 subjects. Optimal paper speed is that speed where the 3 observers are in closest agreement, that is the speed with the smallest mean paired observer differences. For both individual points and calculated intervals, the optimal paper speed is seen to be 100 mm/s, particularly after excluding I_M and also IVCT, which depends on I_M. Calculation of intervals substantially reduced mean difference levels determined for points.

PAPER SPEED 25 mm/s

The paper speed with the largest combined point and interval paired observer differences is seen from Table 1 to be 25 mm/s. Considering only *point* measurements, all paired observer differences are largest at this speed. However, this was not quite so for *interval* measurements. For RR, the largest paired observer difference is at 50 mm/s, while the largest values for PTT and IVCT are at 75 mm/s. However at 25 mm/s the second largest values for these 3 intervals are obtained while both PEP and LVET also have the largest difference values at this speed. Yet it is noteworthy that for LVET, the mean difference at 25 mm/s was within only 1·2 ms of the minimal difference at 100 mm/s and not significantly different.

POINT MEASUREMENTS

Since paired observer differences were significant among paper speeds for all the point measurements except I_M (Table 2), the point measurements were analysed again, omitting the values for paper speed 25 mm/s. The results are shown in Table 3. From these data it is probable that the significant differences for point measurements shown in Table 2 are attributable in part to the large paired observer differences at 25 mm/s paper speed. Interval measurements, however, are not amenable to such treatment since larger paired observer differences occur for the RR measurement at 50 mm/s and for the PTT and IVCT at 75 mm/s. It is also noteworthy that a particularly small paired observer difference occurs for the RR interval at 100 mm/s.

Table 2 *Variance of all 5 paper speeds for paired observer differences**

	Mean square	F ratio	P
Points			
R	70·7	7·37	< 0·01
I_M	67·2	2·13	NS
CAR_u	194·4	15·07	< 0·01
II_A	36·1	3·68	< 0·01
CAR_{IN}	111·8	13·31	< 0·01
Intervals			
RR	146·3	7·62	< 0·01
PTT	19·0	5·59	< 0·01
PEP	156·9	12·25	< 0·01
IVCT	83·9	2·78	< 0·05
LVET	9·9	2·25	NS

*Degrees of freedom = 4.

Table 3 *Variance between paper speeds 50, 75, 100, and 200 mm/s for paired observer differences**

	Mean square	F ratio	P
R	9·7	0·64	NS
I_M	47·9	0·17	NS
CAR_u	6·8	0·86	NS
II_A	13·5	0·83	NS
CAR_{IN}	11·2	0·93	NS

*Degrees of freedom = 3.

Discussion

The results support rejection of the 25 mm/s paper speed for the time based measurements. The obvious exception is electrocardiography where it is the standard paper speed with measurements made to a precision of 10 ms. Yet the results support our previous study that showed a paper speed of 25 mm/s to be satisfactory for the determination of LVET—the only interval where paired observer differences were not significantly different among all 5 paper speeds. This is not surprising since the two point measurements used for the calculation of the LVET are both easily discernible at all speeds. Indeed, most LVETs lie between 260 and 300 ms. Even if the differences were significant, measurement at 25 mm/s would introduce an error of well under 1 per cent. This is not true for the first heart sound where even small degrees of baseline perturbation, compression of the successive vibrations, and any amplitude reduction renders point recognition difficult for I_M. Thus, it is not surprising that relatively poor results were obtained for I_M and IVCT. This has been widely recognised intuitively, leading to omission of qI_M and IVCT from most systolic time interval measurement.

VARIANCE OF SUBJECTS AND THE THREE PAIRED OBSERVER DIFFERENCES

The variance of the paired observer differences between subjects and the variance between the 3 groups of paired observer differences is presented in Table 4. For all points and intervals there were significant differences between the paired observer differences for the 10 subjects. Inspection of the original data revealed that no single subject was apparently responsible for these significant differences nor was there a preponderance of large values for the paired observer differences in either the healthy volunteers or the subjects with known cardiac disease.

Table 4 *Subject variance for paired observer differences**

	Mean square	*F ratio*	*P*
qR	67·0	6·98	< 0·01
I_M	327·3	10·39	< 0·01
CAR_u	46·1	3·58	< 0·01
II_A	117·4	11·98	< 0·01
CAR_{IN}	98·2	11·69	< 0·01
RR	157·0	8·18	< 0·01
PTT	25·7	7·56	< 0·01
PEP	41·2	3·22	< 0·01
IVCT	586·4	19·42	< 0·01
LVET	53·9	12·26	< 0·01

*Degrees of freedom = 9.

INTERACTIONS

Interactions for the paired observer differences are shown in Table 5. Except for PTT and LVET, none of the other 8 points or intervals show interactions between the 3 groups of paired observer differences and the 5 paper speeds (Table 5A). This indicates that all observers were affected by paper speed in the same manner. There was significant interaction between paper speed and subjects for the paired observer differences for all point measurements except CAR_u and all intervals (Table 5B). The implication is that the effect of paper speed on certain subjects is not the same for all subjects. Finally, except for RR, all point measurements and derived intervals showed significant interaction between the 3 groups of paired observer differences and the 10 subjects (Table 5C) presumably because

Table 5 *Interactions for paired observer differences*

	Mean square	*F-ratio*	*P*		*Mean square*	*F-ratio*	*P*
(A) *Between 3 groups of paired observer differences and 5 paper speeds**							
RR	15·6	1·62	NS	RR	25·5	1·33	NS
I_M	21·2	0·67	NS	PTT	7·0	2·07	< 0·05
CAR_u	17·0	1·32	NS	PEP	7·9	0·62	NS
II_A	12·8	1·31	NS	IVCT	16·8	0·56	NS
CAR_{IN}	6·7	0·55	NS	LVET	10·9	2·47	< 0·05
(B) *Between 5 paper speeds and 10 subjects†*							
RR	18·1	1·89	< 0·01	RR	101·2	5·27	< 0·01
I_M	77·3	2·45	< 0·01	PTT	15·1	3·07	< 0·01
CAR_u	17·8	1·38	NS	PEP	33·6	2·63	< 0·01
II_A	36·1	3·68	< 0·01	IVCT	99·9	3·31	< 0·01
CAR_{IN}	20·5	2·44	< 0·01	LVET	20·5	4·67	< 0·01
(C) *Between 3 groups of paired observer differences and 10 subjects‡*							
RR	26·6	2·77	< 0·01	RR	36·7	1·91	NS
I_M	85·5	2·71	< 0·01	PTT	7·6	2·25	< 0·01
CAR_u	42·3	3·28	< 0·01	PEP	36·1	2·82	< 0·01
II_A	20·5	2·10	< 0·01	IVCT	161·9	5·36	< 0·01
CAR_{IN}	25·9	3·08	< 0·01	LVET	16·4	3·72	< 0·01

*Degrees of freedom = 8.
†Degrees of freedom = 36.
‡Degrees of freedom = 18.

Table 6 *Variability between all 5 paper speeds for paired observer differences*

	Measurements from initiation of q wave			Measurements from peak of R wave	
	Mean	P		Mean	P
RR	5·7	< 0·01		—	—
I_M	11·7	NS	R-I_{MM}	9·6	NS
CAR_u	7·0	< 0·01	R-CAR_u	4·6	NS
II_A	7·1	< 0·01	R-II_A	3·6	< 0·01
CAR_{IN}	7·4	< 0·01	R-CAR_{IN}	2·5	< 0·01

one or two of the observers identified points inconsistently for a given subject. No attempts, however, were made in this study to elucidate the origins of significant interactions when present.

QR MEASUREMENT

To define better the source of large values for paired observer differences, we decided to examine the effects of removal of the QR for point measurements, since in these cases QR is an integral portion of the final value. This resulted in all point measurements being determined from the peak of the R wave as well as QR. Table 6 shows the mean paired observer differences over all 5 paper speeds. The result was smaller paired observer differences for all point measurements. We may thus conclude that some portion of the error made in point measurements resides in the determination of the onset of the Q wave. Though significant differences between paired observer differences existed for R-II_A and R-CAR_{IN}, the absolute magnitude of these differences was very small.

References

Lewis, R. P., Rittgers, S. E., Forester, W. R., and Boudoulas, H. (1977). A critical review of systolic time intervals. *Circulation*, **56**, 146-158.

Pigott, V. M., Ryan-Platt, R., Elber, E., and Spodick, D. H. (1972). The influence of recording speed on apexcardiographic timing: a multi-observer study of precision and performance utilizing randomized traces in multiple subjects. *Cardiology*, **57**, 232-239.

Spodick, D. H., Kumar, S., Flessas, A. P., Sriratanaban, A. D., Sosler, G., Klints, R. V., and Muench, H. (1969). The relationship of paper speed to precision of pulse wave measurements: a multiple observer study of left ventricular ejection time. *Aerospace Medicine* **40**, 707-709.

Requests for reprints to Professor David H. Spodick, Division of Cardiology, St Vincent Hospital, 25 Winthrop Street, Worcester, Massachusetts 01604, USA.